Reconciling Alternative Estimates of the Net Energy Balance of Ethanol Produced from Corn and Biodiesel Produced for Soybean Oil

**A Review Prepared by the Office of the Chief Economist,
U.S. Department of Agriculture, Washington, DC 20250
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Overview

In the March 2005 issue of the journal *Natural Resources Research*, an article entitled "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower" by David Pimentel and Tad W. Patzek found the energy outputs from both ethanol and biodiesel were less than the energy needed to produce ethanol and biodiesel. In this paper we compare the results from Pimentel and Patzek to findings which demonstrate the energy outputs from both ethanol and biodiesel were greater than the energy need to produce them. We believe the evidence demonstrates Pimentel and Patzek overestimate the amount of energy needed to grow corn and convert corn to ethanol. The same is true for soybeans and biodiesel.

Ethanol

The Pimentel and Patzek estimated negative net energy balance from ethanol production using corn as a feedstock is in stark contrast to recent estimates in a study by the Hosein Shapouri and Andrew McAloon of the U.S. Department of Agriculture (USDA) and a study by Michael Wang at the Argonne National Laboratory's Center for Transportation Research.[1] Both the USDA study and the study by Wang show the energy output from ethanol was substantially greater the fossil energy needed to produce ethanol. Table 1 presents information on the energy needed to produce ethanol from corn from the Pimentel and Patzek study and the USDA study to illustrate and explain the differences between both studies.

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[1] The study by Shapouri and McAloon, "The 2001 Net Energy Balance of Corn-Ethanol" is available at the USDA, Office of Energy Policy and New Uses web site: http://www.usda.gov/oce/oepnu/. The Wang study can be found at the following web site: http://www.transportation.anl.gov/research/systems_analysis/fuel_ethanol.html.

Table 1. Comparison of the Pimentel and Patzek results to the USDA results.

Process	Pimentel and Patzek [2]	USDA [3]	Difference
	Btu per Gallon of Ethanol		
Corn Production	37,860	18,713	-19,147
Corn Transportation	4,834	2,120	-2,714
Ethanol Conversion	56,399	51,220	-5,179
Energy Input Excluding Coproducts	99,093	72,053	-27,040
Coproduct Value	6,680	26,250	19,570
Energy Input Including Coproducts	*92,413*	*45,803*	*-46,610*
Total Energy Output	*77,011*	*76,330*	*-681*
Net Energy Balance	**-15,402**	**30,527**	**45,929**

Pimentel and Patzek found the energy needed to produce ethanol from corn exceeded the energy output from ethanol, resulting in a net energy balance of about -15,400 Btu (British thermal units) per gallon of ethanol. In the USDA study, the energy needed to produce ethanol from corn was less than the energy output from ethanol, resulting in a net energy balance from ethanol of about +30,000 Btu per gallon of ethanol.

The almost 45,000 Btu difference between the Pimentel and Patzek study and the USDA study can be explained by major differences in the energy needed to produce corn, the energy required to convert corn to ethanol, and energy value associated with the production of ethanol coproducts. USDA estimated the energy necessary to produce corn to be about half the amount estimated by Pimentel and Patzek. The ethanol conversion process used about 10 percent less energy in the USDA study compared to the Pimentel and Patzek study. The energy credit associated with ethanol coproducts was over 3.5 times greater in the USDA study compared to the Pimentel and Patzek study. To explain these differences we look at each of these components in further detail.

Energy Necessary to Produce Corn. Pimentel and Patzek found the energy needed to grow corn accounted for 37,860 Btu of the energy required to produce a gallon of ethanol compared to about 19,000 Btu in the USDA study. Table 2 compares the amount of energy used

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[2] Pimentel and Patzek report their results (Table 2 of their paper) in kcal x 1000 per 1000 liters of ethanol. Converted to Btu per gallon using 1 liter = 0.26 gallons and 1 kcal = 3.96 Btu.

[3] Estimates are based on a weighted average of dry and wet milling. Ethanol conversion includes 1,588 Btu per gallon for ethanol distribution.

Table 2. Comparison of Amount of Energy Used to Produce Corn.

Input	Pimentel and Patzek[4]	USDA	Difference
	Btu per Gallon of Ethanol from Corn Production		
Labor	2,155	0	-2,155
Machinery	4,749	0	-4,749
Diesel	4,679	2,816	-1,864
Gasoline	1,890	1,323	-567
Nitrogen	11,421	8,824	-2,597
Phosphorus	1,260	613	-647
Potassium	1,171	714	-457
Lime	1,470	24	-1,446
Seeds	2,426	227	-2,199
Irrigation	1,493	62	-1,431
Herbicides	2,893	1,105	-1,787
Insecticides	1,306	--	-1,306
Electricity	159	849	690
Transport	788	76	-713
LP Gas		792	792
Natural Gas		694	694
Custom Work		594	594
Total	37,860	18,713	-19,147

to produce corn from both studies and shows Pimentel and Patzek allocate a larger amount of energy for almost every input used in corn production compared to the USDA study.

   Labor. Pimentel and Patzek assume 4.62 hours of labor and $60 labor expenses per acre of corn, which resulted in assigning 0.746 million Btu per acre or 2,155 Btu per gallon to labor use. The USDA study excludes energy used by labor due to the unavailability of a reliable estimate. However, data from the USDA's Economic Research Service (ERS) cost of production estimates show, in 2001, expenditures for hired labor per acre of corn were about $3 per acre. USDA/ERS cost of production estimates are based on surveys of farms conducted as part of the part of the Agricultural Resource Management Survey (ARMS).[5] For 2001, ERS also allocated about $25 per acre for the opportunity cost of unpaid labor. Therefore, based on the

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[4] The amount of Btu per gallon of ethanol for each corn input is calculated by taking the share of energy used to produce corn (Table 1 in Pimentel and Patzek) and applying that share to the total amount of energy from corn in ethanol production (Table 2 in Pimentel and Patzek).

[5] More information regarding the ERS cost of production estimates can be found at the following web site: http://www.ers.usda.gov/briefing/farmincome/costsandreturns.htmhttp://www.ers.usda.gov/briefing/cos tsandreturns.htm. The theoretical basis and accounting methods used for estimating the costs and returns are consistent with standards recommended by the American Agricultural Economics Association (AAEA) Task Force on Commodity Costs and Returns.

ERS data, total labor costs (hired plus unpaid) in 2001 were about $28 per acre, significantly less than the $60 estimate used by Pimentel and Patzek. Even if the USDA study allocated energy to labor, the $28 per acre expenditure equates to about 2 hours of labor per acre over the year. Assuming farm labor requires 4,000 calories per day, 2 hours per acre translates into only 330 calories per acre over the year (2/24 x 4,000). Therefore, the estimated energy for labor would be only a fraction of that used by Pimentel and Patzek.

Machinery. In addition, Pimentel and Patzek assigned 1.62 million Btu per acre or 4,479 Btu per gallon ethanol for farm machinery and farm equipment. The reference for energy used for farm machinery energy was from a paper by Pimentel in 1996. The USDA study excludes energy used in farm machinery and farm equipment due to the unavailability of a reliable estimate.

Diesel Fuel and Gasoline. Pimentel and Patzek also assumed 9.41 gallons of diesel fuel and 4.3 gallons of gasoline per acre of corn. Therefore, diesel fuel and gasoline accounted for about 6,500 Btu of the total amount of energy to produce a gallon of ethanol. The USDA study based their estimate of diesel fuel and gasoline on data collected by the USDA/ERS ARMS. Results from ARMS showed, in 2001, U.S corn growers used, on average, only 6.2 gallons of diesel fuel and 1.7 gallons of gasoline per acre, respectively. Therefore, the amount of energy used to produce ethanol attributed to diesel fuel and gasoline is significantly lower in the USDA study. Data on energy use by major field crop can be found at the ERS web site: http://www.ers.usda.gov/data/costsandreturns/testpick.htm.

Nitrogen, Phosphorus, and Potassium (Potash). The production of nitrogen fertilizer requires a large amount of energy, mostly in the form of natural gas. Pimentel and Patzek assumed 28,989 Btu per pound of nitrogen, 7,526 Btu per pound of phosphorus (P_2O_5), and 5,906 Btu per pound of potash (K_2O), respectively. In 2004, USDA asked Dr. Keith Stokes, President of the Stokes Engineering Company and fertilizer expert, to estimate energy used in production of nitrogen, phosphate and potash fertilizers. Dr. Stokes' estimates on energy used to make and deliver nutrients were 24,500 Btu per pound of nitrogen, 4,000 Btu per pound of P_2O_5, and 3,000 Btu of K_2O.

Lime. Pimentel and Patzek assumed 998 pounds of lime is applied per acre of corn production which assigned more than 500,000 Btu per acre or 1,470 Btu per gallon of ethanol to lime. Pimentel and Patzek estimated the cost of lime at $11 per acre. The USDA study based their estimate of the amount of lime used in corn production on the USDA/ERS cost of production data and ARMS. The USDA/ERS cost of production estimates indicate corn farmers spend only about $0.12 per acre on soil conditioners (e.g., lime) and U.S. corn farmers use, on average, only 16 pounds of lime per acre. Based on the USDA/ERS data, the USDA study assigned 8,757 Btu of lime per acre, which translated into about 24 Btu per gallon of ethanol.

Irrigation. Pimentel and Patzek assumed 8.1 centimeter of irrigation with an energy value of 0.516 million Btu per acre or about 1,493 Btu per gallon of ethanol. However, data collected by the USDA/ERS ARMS showed less than 15 percent of the corn crop was irrigated. Energy used for irrigation was reported in direct energy used in corn production by USDA.

The USDA study estimated the total direct and indirect energy inputs used in production of corn in 2001 was 49,753 Btu per bushel or about 19,000 Btu per gallon of ethanol produced. The amount of energy used to produce a bushel of corn according to Pimentel and Patzek was more than 95,000 per bushel or almost 38,000 Btu per gallon of ethanol produced; about twice as high as the USDA estimate. One reason Pimentel and Patzek over estimate the amount of energy used in corn production is some of their data are outdated and do not incorporate the improvement in energy efficiency used to produce crops over time. A second reason Pimentel and Patzek over estimate the amount of energy used in corn production is the data they use are not based on a consistent set of cropping practices. The USDA study, because it relies primarily on data from the USDA/ERS ARMS, is more representative of actual production practices across the United States.

Energy Necessary to Convert Corn to Ethanol. Pimentel and Patzek also overestimated the energy used in the conversion of corn to ethanol. Pimentel and Patzek found it took about 56,000 Btu of energy to process corn to one gallon of ethanol; more than 5,000 Btu higher than the USDA estimate of about 51,000 Btu per gallon (including ethanol distribution). In 2001, USDA asked BBI International to survey ethanol plants to estimate the Btu of thermal energy and kilowatt hours (kwh) of electricity used per gallon of ethanol. That analysis indicated that, on average, dry mill ethanol plants used 1.09 kilowatt hour (kwh) of electricity and 34,700 Btu of thermal energy to produce each gallon of ethanol. When energy losses to produce electricity and natural gas were taken into account, the average dry mill ethanol plant consumed about 47,116 Btu of primary energy per gallon of ethanol produced. Energy used in wet mill ethanol plants per gallon of ethanol averaged 52,349 Btu. The weighted average for the industry was 49,733 Btu per gallon of ethanol produced. Adding the approximately 1,500 Btu per gallon for ethanol distribution resulted in a total amount of about 51,000 Btu of energy to produce each gallon of ethanol.

Energy Embodied in Ethanol Coproducts. To estimate the net energy balance associated with ethanol, a portion of the total energy used in ethanol production must be allocated to coproducts such as corn gluten meal, corn gluten feed, corn oil and distillers dried grains. Pimentel and Patzek assigned only 6,700 Btu of total energy to coproducts.

USDA allocates the energy used in ethanol production and coproducts through process and cost models developed by the USDA's Agricultural Research Service (ARS). ARS has a research program involved in the production of ethanol and other renewable fuels, and part of this program has been dedicated to creating process and cost models that allow researchers to identify the production cost and energy consumption associated with each step of the ethanol production process.[6] The models are based on data from ethanol producers, engineering firms, equipment manufacturers, and commercially available computer software for chemical process design and costing.

The ARS production models estimate over 40 percent of the energy used to produce ethanol is required for the production of coproducts. The 40 percent estimate is conservative because

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[6] Information about the ARS process engineering unit can be found at:
http://www.arserrc.gov/ccse/EngineeringSupportGroup.htm

ethanol plants rely on techniques referred to as heat integration which is the reuse of energy for different tasks. Therefore, some of the energy used in the ethanol process will also be used in coproduct drying operation. Because the ARS models allocate energy to the first step in the overall production process, the models allocate a larger share of energy to ethanol and a smaller share of energy to coproducts compared to an allocation method which prorates the energy over the different tasks. Hence, USDA's estimates of energy allocated to coproducts, while greater than Pimentel and Patzek, may underestimate the energy actually used to produce coproducts.

Comparison to Gasoline

An analysis by Michael Wang at the Argonne National Laboratory's Center for Transportation Research also found the energy output from ethanol was substantially greater the fossil energy needed to produce ethanol. Based on a peer-reviewed model named GREET (Greenhouse gases, Regulated Emissions and Energy used in Transportation), Wang found that 0.74 million Btu of fossil energy were used to produce 1 million Btu of ethanol (for comparison, the USDA study estimated that about 0.6 million Btu of fossil energy were used to produce 1 million Btu of ethanol).[7] The estimation of net energy balance on its own, however, is not a particularly useful concept. What is more important is the value energy has to society and how it compares to alternatives. Wang compared his results to gasoline where 1.23 million Btu of fossil energy are consumed for each 1 million Btu of gasoline delivered.

Wang noted "confusion arises because a portion of the *total* (not fossil or petroleum) energy input in the ethanol cycle is the "free" solar energy that ends up in the corn. Since the solar energy is free, renewable, and environmentally benign, it should not be taken into account in the energy balance calculations." Wang further noted "While the *total* (includes solar) energy needed to produce a unit of ethanol is more than the *total* energy needed to produce a unit of gasoline, ethanol is superior when GREET calculates either (1) the amount of *fossil* energy needed or (2) the amount of *petroleum* energy needed." A U.S. Department of Energy (DOE) brochure which highlights the ethanol life-cycle results using the GREET model can be found at: http://www.eere.energy.gov/vehiclesandfuels/pdfs/program/2005_ethanol_brochure.pdf.

Biodiesel

Pimentel and Patzek also concluded the energy balance of biodiesel is negative. The authors presented data in their March 2005 article (Tables 6 and 7) on soybean production and processing that led them to conclude that making biodiesel from soybean oil results in a net energy loss of 32 percent. When taking a coproduct credit of 8.7 million Btu for soybean meal, Pimentel and Patzek concluded the net energy loss for biodiesel is 8 percent.[8] However, Pimentel and Patzek appear to have made an error when calculating their net loss ratios (page 72 of their article). As shown below, the correct calculations, using Pimentel and Patzek estimates,

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[7] The GREET model, including documentation and results can be found at the following web site: http://www.transportation.anl.gov/software/GREET/publications.html

[8] Pimentel and Patzek report their results in kcal. 1 kcal = 3.9656 Btu.

result in an energy loss of 27 percent and only 2 percent when a coproduct credit is added to the formula.

Energy ratio without coproduct credit

1) Net energy value =   Energy output – Energy input
              35.7 million Btu – 45.2 million Btu = - 9.5 million Btu
2) Net energy ratio = Net energy value ÷ Energy output
              - 9.5 million Btu ÷ 35.7 million Btu = - 0.266 or – 27 percent

Energy ratio with coproduct credit

3) Net energy value = 35.7 million Btu – (45.2 million Btu – 8.7 million Btu) = - 0.8 million Btu
4) Net energy ratio =   - 0.8 million Btu ÷ 35.7 million Btu = - 0.022 or -2.2 percent

When correcting the apparent errors, Pimentel and Patzek's data show the energy loss of biodiesel made from soybean oil is about 2 percent.   A 2 percent energy loss is relatively efficient, since petroleum diesel has an energy loss of about 17 percent (Sheehan et al.). Thus, data from Pimentel and Patzek's analysis indicates biodiesel uses about 15 percent less energy than petroleum diesel.

Although Pimentel and Patzek conclude the energy balance of biodiesel using soybeans is only slightly negative, other studies indicate a highly positive net energy ratio (Sheehan et al.[9]; Ahmed et al.[10]; and International Energy Administration[11]). The most recent comprehensive study conducted in the United States titled L*ife Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus* concluded the net energy ratio of biodiesel made from soybeans was +3.2 or +320 percent (Sheehan et al.). Comparing this study with Pimentel and Patzek's analysis reveals major discrepancies in the data and assumptions used by Pimentel and Patzek, which are outlined below.

Energy Necessary to Grow Soybeans.   Table 3 shows on-farm energy used to grow soybeans as reported by Sheehan et al. and Pimentel and Patzek. Sheehan et al. used data from USDA's 1990 ARMS, formerly called the Farm Cost and Returns Survey, which was the most current source of farm input data available for soybean production at the time of the study. The ARMS estimates for energy use on soybean acreage are reported in *Soybeans: State-Level*

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[9] Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., and Shapouri, H. (1998). *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*. NREL/SR-580-24089. U.S. Department of Energy, Office of Fuels Development and U.S. Department of Agriculture, Office of Energy, May, 1998.

[10] Amed, I., Decker, J., and Morris, D., (1994). *How Much Energy Does It Take to Make a Gallon of Soydiesel?* Institute of Local Self Reliance. January 1994.

[11] International Energy Agency (2004). *Biofuels for Transport: An International Perspective*. The Organization of Economic Cooperation and Development, International Energy Agency.

Production Costs, Characteristics, and Input Use, 1990, by Ali and McBride.[12] The 1990 survey represented about 272,000 farms that planted soybeans on 44 million acres and produced 1.4 billion bushels, accounting for approximately 75 percent of U.S. soybean production. Pimentel and Patzek also use data from the Ali and McBride report and various other sources.

Table 3. Comparison of Pimentel and Patzek results with Sheehan et al.

Input	Units	Pimentel and Patzek	Sheehan et al
Labor	hours per acre	2.9	0
Machinery	pounds per acre	17.9	0
Diesel	gallons per acre	4.16	5.29
Gasoline	gallons per acre	3.82	3.11
LP Gas	gallons per acre	0.35	0.38
Natural Gas	cubic ft per acre	0.00	0.07
Nitrogen	pounds per acre	3.30	9.89
Phosphorus	pounds per acre	33.73	31.02
Potassium	pounds per acre	13.21	52.8
Lime	pounds per acre	4,284	0
Seed	pounds per acre	61.85	62.66
Herbicide	pounds per acre	1.16	4.02
Insecticide	pounds per acre	0.00	0.04
Electricity	kWh per acre	4.05	4.6

Lime. Table 3 shows a major difference between the two studies is the estimates used for lime application. Pimentel and Patzek reported soybeans require 4,284 pounds of lime per acre, compared to zero pounds per acre reported by Sheehan et al. Farmers occasionally apply lime to soils to improve soybean yield, but rarely on an annual basis. Data collected by the ARMS indicates lime is a relatively minor input and lime application rates were not included in the Ali and McBride report, which was the soybean production data source used by Sheehan et al. The source of Pimentel and Patzek's lime application data is a 1999 Iowa State University (ISU) study that investigated corn and soybean yield responses to various lime application rates under soil conditions and management systems typical of northwestern Iowa (Kassel and Tidman[13]). The study was conducted at an ISU research farm to investigate optimal lime application rates for corn-soybean rotations. The study does not report actual lime use, although current recommendations suggest producers in northwestern Iowa need 5,000 to 6,000 pounds of lime per acre to correct pH in their soil for several years. The study design was clearly not intended to provide results representing annual lime application rates on U.S. soybean acreage.

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[12] Ali, M., and McBride, W. (1994). *Soybeans: State-Level Production Costs, Characteristics, and Input Use, 1990.* U.S. Department of Agriculture, Economic Research Service, SB-873, 1994.

[13] Kassel, P., and Tidman, M. (1999). *Ag Lime Impact on Yield in Several Tillage Systems.* Integrated Crop Management, Iowa State University.

The experimental data used by Pimentel and Patzek on lime application rates is specific to northwestern Iowa and does not provide the same type of information as the ARMS data. The primary intent of the ARMS is to generate data that represents the typical acre of soybeans grown in the United States. In the 2002 ARMS, about half of all farmers reported using lime on soybean acres and the other half have never applied lime to their soil. The average application rate on those acres that received lime was about 2 tons per acre. However, farmers that added lime to their soil, only added it once every 3 to 5 years (McBride[14]). When factoring in this annual frequency rate and looking across all soybeans (not just those acres that received lime in a given year) the lime application rate for soybeans was about 20 pounds per acre (McBride).

Using misspecified data on lime application resulted in a major error in Pimentel and Patzek's analysis. They incorrectly concluded lime was by far the largest energy input, accounting for 36 percent of the energy required to grow soybeans. In reality, lime is the smallest energy input used to grow soybeans. Had Pimentel and Patzek used the ARMS data, the energy requirement for lime would have been only about 4,600 Btu per acre instead of the 2.2 million Btu per acre they report. This correction alone would have reduced the energy required to grow soybeans from 6 million Btu per acre to less than 4 million Btu per acre and would make Pimentel and Patzek's overall energy balance estimate for biodiesel positive.

Energy Embodied in Farm Labor. Pimentel and Patzek estimated the labor used to grow soybeans at 1.1 million Btu per hectare or 2.3 million Btu per metric ton of biodiesel. In terms of energy use, Pimentel and Patzek rank labor energy higher than gasoline, LP gas, and nitrogen fertilizer. Labor is about 7.6 percent of the energy needed for growing soybeans and about 5 percent of total energy needed to produce biodiesel. Pimentel and Patzek do not provide details on how this number is derived, but base it on their assumption that a person works 2,000 hours per year utilizing an average 8,000 liters of oil equivalent. Sheehan et al. do not allocate any energy to labor and it is rarely included in other studies. The energy consumed by workers to support their life-style is not determined by occupation and reducing labor time for soybean production would not result in energy savings.

Energy Embodied in Farm Machinery. Pimentel and Patzek also include energy used to manufacture farm machinery in their analysis. Their estimate for energy embodied in machinery adds about 3.0 million Btu or almost 10 percent to the energy required to grow soybeans for a metric ton of biodiesel. Sheehan et al. viewed the energy embodied in farm machinery as insignificant and it was excluded from their system boundary. Energy used in manufacturing farm equipment is difficult to quantify, due to the large amount and diversity of use of farm equipment used by a typical farmer. Little research has been done in this area, so reliable estimates are unavailable. Since the energy embodied in farm equipment is very small, it is not worth the additional time and expense to collect this information (Graboski[15]).

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[14] Personal communication with William McBride at USDA's Economic Research Service.

[15] Graboski, M. (2002). *Fossil Energy Use in the Manufacture of Corn Ethanol.* Prepared for the National Corn Growers Association, May 2002.

Energy Used for Processing Soybeans into Biodiesel. Processing soybeans into biodiesel requires two steps. Soybeans are first crushed and then the soybean oil is converted to biodiesel.

Energy Used for Soybean Crushing. Pimentel and Patzek report the soybean crushing process requires about 3.6 million kcal to produce a metric ton of soybean oil. According to Sheehan et al., the energy used for crushing soybeans is much smaller than reported by Pimentel and Patzek. For example, Pimentel and Patzek report that one metric ton of soybean oil requires 270 kWh of electricity compared to 70 kWh reported by Sheehan et al. About 5.2 million Btu of steam is required by Pimentel and Patzek's crushing plant, compared to only about 870,000 Btu of steam reported by Sheehan et al. The natural gas estimate used by Pimentel and Patzek is about 65 percent higher than the natural gas estimate used by Sheehan et al. Pimentel and Patzek include several energy inputs that are not included in the Sheehan et al. analysis. For example, Pimentel and Patzek calculate the amount of energy used to produce the building materials for the plant and plant equipment. Sheehan et al. viewed the energy embodied in building materials and plant equipment to be outside their system boundary. Reliable data for these inputs are difficult to obtain and since the energy embodied in these materials are very small, most researchers exclude them from their analysis. An investigation by Boustead found the energy used to construct large equipment and facilities is less than 0.01 percent for any product.[16] The energy requirements reported by Pimentel and Patzek for equipment and facilities are about four percent of total energy requirements.   However, their estimates are derived from a 1979 study, which probably does not reflect today's U.S. manufacturing sector. Increasing energy costs and competition from abroad has caused most U.S. manufacturers to become much more energy efficient over the past 25 years. For example, the energy used to produce steel has fallen by more than 45 percent since 1975 (Graboski[17]).

Energy Used for Converting Oil into Biodiesel. Pimentel and Patzek completed their analysis after the crushing step and do not report energy requirements for processing soybean oil into biodiesel. It is not clear why their analysis ignores this important step. Biodiesel is made by modifying the oil through a process called transesterification, which reacts a vegetable oil or fat with an alcohol in the presence of a catalyst, resulting in the production of biodiesel and glycerol. Sheehan et al. developed a model to estimate the energy required to process soybean oil into biodiesel using transesterification. While Pimentel and Patzek's energy requirements for crushing soybeans was much higher than the Sheehan et al. estimate, this difference was greatly offset by the transesterification energy requirements included in the Sheehan et al. study.

Coproduct Allocation. Much of the difference between the two studies can be explained by the calculation used to estimate the coproduct credit for soybean meal. The energy used for crushing soybeans results in the production of soybean meal and soybean oil. Soybean meal is the most valuable product derived from soybean processing and is primarily used as an animal feed. Soybean oil is used mostly for edible purposes, but it also has many industrial uses,

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[16] Boustead, I. (1997). *Eco Profiles of the European Plastics Industry.* Report #15: Nylon 66. Association of Plastics Manufacturers in Europe, October 1997.

[17] Graboski, M. (2002). *Fossil Energy Use in the Manufacture of Corn Ethanol.* Prepared for the National Corn Growers Association, May 2002.

including biodiesel. The energy assigned to biodiesel from the crusher should only relate to the energy used to produce the oil. Likewise, the energy used to grow soybeans must also be allocated between soybean meal and soybean oil. Thus, the question is how to separate the energy used for soybean meal from the energy used to produce the oil. Sheehan et al. use an allocation method based on the mass output of each coproduct. The mass output between the two products is 18 percent for the oil and 82 percent for the meal. Therefore, 18 percent of the energy used for soybean production and processing is allocated to biodiesel.

Pimentel and Patzek do not provide a description of their allocation method. They simply state a credit should be taken for the soybean meal and this has an energy value of 8.7 million Btu per metric ton of biodiesel. This credit is equivalent to about 19 percent of their total energy requirement for biodiesel. If Pimentel and Patzek had used the mass allocation method used by Sheehan et al. (82 percent credit for soybean meal), Pimentel and Patzek's total energy requirement would have been reduced from 45.2 million Btu per metric ton of biodiesel to about 8.3 million Btu per metric ton of biodiesel. Had Pimentel and Patzek used the mass allocation method to estimate the coproduct credit for soybean meal, the energy output associated with biodiesel (35.7 million Btu per metric ton of biodiesel) would have been 4.3 times greater than the energy input requirements (8.3 million Btu per metric ton of biodiesel).

Conclusion

We believe Pimentel and Patzek overestimate the amount of energy needed to grow corn and convert corn to ethanol. The same is true for biodiesel. In our estimates, the energy output from both ethanol and biodiesel were greater than the fossil energy need to produce them. However, a fundamental flaw in using energy balance is that all energy has the same value. As discussed by Ernst Berndt[18] "Value is a multi-dimensional phenomenon. Attributes such as weight, cleanliness, safety, heat content, security of supply, amenability to storage, relative costs of conversion and cooperating end-use technology, and capacity to do useful work are all important; the various energy types (coal, crude oil, natural gas, electricity) differ in their attribute contributions, and so their value to society also varies." We suggest that adding the other attributes of ethanol such as its contribution to cleaner air would make ethanol and biodiesel even more attractive to fuels.

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[18] Berndt, Ernst R. "From Technocracy to Net Energy Analysis: Engineers, Economists and Recurring Energy Theories of Value" Massachusetts Institute of Technology. Studies in Energy and the American Economy. Discussion Paper No. 11. MIT-EL 81-065WP. September 1982.